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Simulation study on supply temperature optimization of university campus heating system

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Abstract

The article deals with optimizing supply temperature at the district heating plant using simulations. It describes a new method of supply temperature optimization based on penalty functions considering indoor temperature and heat energy consumed. According to the method proposed the supply temperature is calculated and adjusted for maintaining the most comfortable indoor temperature in the buildings which lack an automated individual heating system. The article offers a scheme of the heating plant model predictive control making use of the optimization method developed.

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Keywords: temperature optimization; district heating; heating system; supply temperature; simulation; university campus

1. Introduction

District heating systems are widely used in cities over the world [1]. Such systems are composed of one or several heating plants and plenty of consumers linked with the help of pipelines. Consumers of such systems are different purpose facilities [2]: manufacturing units, shopping complexes, educational institutions, office and apartment buildings, etc. Along with it heat energy consumers may be equipped with automated individual heating system (IHS) operated by local controller in order to distribute heat energy to domestic hot water and heating systems [3].

However, big district heating systems are characterized by consumers which often may not be equipped with an automated IHS. In this case there is applied central temperature control strategy which makes it possible to regulate

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heat energy supply by changing the supply temperature [4]. This stipulated the task to maintain supply temperature which will be enough to provide all the users with heat energy they need.

The first problem solution was implementing control curves which reflect dependence between supply temperature and outdoor temperature. This solution, in fact, proved to be fairly good [5]. However, due to automated systems development it became possible to get access not only to current and statistic information on consumers' state and characteristics [6-9] but to methods and tools for simulating of consumption parameters and heat energy distribution [10-12].

Simulation brought in ample opportunities for heat energy supply management. In the abovementioned task context simulation allowed quick calculation of the supply temperature sufficient for maintaining required parameters in the nodes of the pipelines network, pointed out by a simulation tool user, taking into account the current parameters and configuration of the pipeline network and its consumers [13,14]. In particular, this function is performed using Termis Software produced by Schneider Electric [15].

Moreover, along with quick calculation of the heating system state, simulation permits to evaluate the microclimate parameters of the space heated [16]. This work will treat temperature control over heat energy supplied by a heating plant taking into account the indoor temperature of buildings.

2. Optimization problem

In order to increase heat energy consumption efficiency for a heating system, two tasks are solved:

- Minimization of heat energy consumption;
- Maximization of heat energy supply quality by maintaining comfortable microclimate.

In the district heating systems the main parameter regulated at heating plants is temperature of the heat energy T_{1S}, supplied to the heating system. The heat medium temperature at building inlets depends on T_{1S}, but it is lower than T_{1S}, due to heat losses when transferred through the pipeline system from heating plants to consumers.

Building heat energy consumption Q_D (Gcal) can be estimated according to [17] as follows:

$$Q_{\mathrm{D}} = (T_1 - T_{\mathrm{OUT}})/(1/(k \cdot \mathrm{F}) + 1/(2 \cdot \mathrm{G}) + 1/\mathrm{q}), \tag{1}$$

where T_1 is the heat medium temperature at the building inlet, T_{OUT} is the outdoor temperature, k is the heat transfer coefficient of radiators, F is the heating area of radiators, G is the heat medium flow rate, q is the heat transfer coefficient of the building.

Heat losses Q_L of the building can be estimated according to [17] as follows:

$$Q_{\mathrm{L}} = q \cdot (T_{\mathrm{IND}} - T_{\mathrm{OUT}}), \tag{2}$$

where T_{IND} is the indoor temperature.

For heating systems the main indicator of the building microclimate quality is the mean indoor temperature T_{IND} which one can get using Eq. 1 after substituting Eq. 2 according to heat balance ($Q_D = Q_L$):

$$T_{\mathrm{IND}} = T_{\mathrm{OUT}} + (T_1 - T_{\mathrm{OUT}})/(q \cdot (1/(k \cdot F) + 1/(2 \cdot G)) + 1). \tag{3}$$

To calculate parameters of heating system consumers (T_1 и G) as a function of the supply temperature T_{1S}, a simulation macro-model was used. The design concept of the macro-model used is described in [18,19]. The macro-model allows calculating state variables of the heating system under the specified characteristics and configurations of the system facilities.

According to Eq. 1 and Eq. 3 the heating plant must produce heat energy Q sufficient for maintaining the most comfortable indoor temperature in each building. This task can be referred to minimax problems of optimization and described using the following system of objective functions:

$$\begin{cases} Q(T_{1S}) \to \min \\ M_{\mathrm{IND}i}(T_{1S}) \to \max, \mathrm{i} = 1..N, \end{cases} \tag{4}$$

where Q is the total heat energy produced, sufficient enough to provide all the buildings connected to the district heating system with heat energy; $M_{\mathrm{IND}i}$ is the assessment of the indoor microclimate quality of the i-building within the heating system; N is the number of buildings connected to the heating system.

To assess the indoor temperature quality R_{1i} of i-building let's employ penalty function R_1 of the indoor temperature which can be described using the following system:

$$R_{1i} = R_1(T_{\mathrm{IND}i}(T_{1S})) = \begin{cases} 1 + p_i \cdot N \cdot (T_{\mathrm{IND}i}^{\min} - T_{\mathrm{IND}i}(T_{1S})), T_{\mathrm{IND}i}(T_{1S}) < T_{\mathrm{IND}i}^{\min} \\ \dfrac{T_{\mathrm{IND}i}(T_{1S}) - T_{\mathrm{IND}i}^{\mathrm{comf}}}{T_{\mathrm{IND}i}^{\min} - T_{\mathrm{IND}i}^{\mathrm{comf}}}, T_{\mathrm{IND}i}^{\min} \le T_{\mathrm{IND}i}(T_{1S}) < T_{\mathrm{IND}i}^{\mathrm{comf}} \\ \dfrac{T_{\mathrm{IND}i}(T_{1S}) - T_{\mathrm{IND}i}^{\mathrm{comf}}}{T_{\mathrm{IND}i}^{\max} - T_{\mathrm{IND}i}^{\mathrm{comf}}}, T_{\mathrm{IND}i}^{\mathrm{comf}} \le T_{\mathrm{IND}i}(T_{1S}) \le T_{\mathrm{IND}i}^{\max} \\ 1 + p_i \cdot N \cdot (T_{\mathrm{IND}i}(T_{1S}) - T_{\mathrm{IND}i}^{\max}), T_{\mathrm{IND}i}(T_{1S}) > T_{\mathrm{IND}i}^{\max} \end{cases}, \tag{5}$$

where $T_{\mathrm{IND}i}(T_{1S})$ is the mean indoor temperature of i-building depending on heating plant supply temperature T_{1S} and taking into consideration heat losses in the pipelines of the heating system. $T_{\mathrm{IND}i}(T_{1S})$ is calculated with the help of the macro-model. $T_{\mathrm{IND}i}^{\min}$, $T_{\mathrm{IND}i}^{\mathrm{comf}}$ and $T_{\mathrm{IND}i}^{\max}$ are, respectively, correspond to minimum, comfortable and maximum indoor temperatures of i-building according to its sanitary regulations; p_i is the penalty coefficient for violating indoor temperature range required (p_i>1).

Fig. 1 represents the penalty function curve of the mean indoor temperature of building.

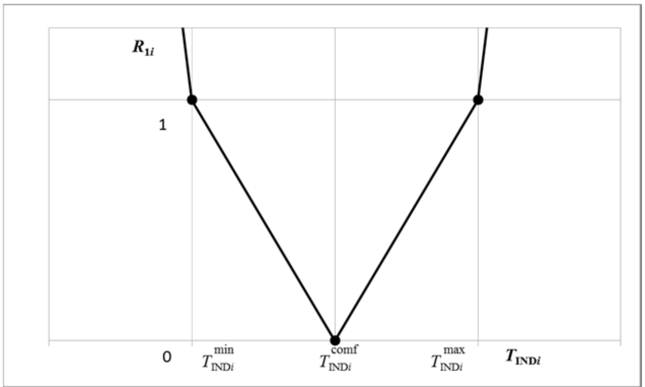

Fig. 1. The penalty function curve of indoor temperature.

To assess heat energy consumed while optimizing the heating plant supply temperature let's introduce penalty function R_2 which can be expressed by the following system:

$$R_2 = \begin{cases} 1 + p \cdot N \cdot (Q^{\min} - Q), Q < Q^{\min} \\ \dfrac{Q - Q^{\min}}{Q^{\max} - Q^{\min}}, Q^{\min} \le Q \end{cases}, \tag{6}$$

where Q is the total heat energy produced; $Q^{\min}$ and $Q^{\max}$ are, respectively, total minimum and total maximum heat energy produced; p is the penalty coefficient for violating minimum heat energy produced (p>1).

The total minimum heat energy produced is the one which is enough to maintain minimum mean indoor temperature for each i-building corresponded to its type (educational institutions, office or apartment buildings, etc.) according to the sanitary regulations. It is calculated while solving the optimization task which follows:

$$Q^{\min} = \begin{cases} Q(T_{1\mathrm{S}}) \to \min \\ T_{\mathrm{IND}i}(T_{1\mathrm{S}}) \geq T_{\mathrm{IND}i}^{\min} \end{cases}, \tag{7}$$

where $Q(T_{1\mathrm{S}})$ is the total heat energy produced by the heating plant and calculated using the macro-model.

The total maximum heat energy produced is the energy sufficient to maintain maximum mean indoor temperature for each i-building corresponded to its type according to the sanitary regulations. It can be found while solving the following optimization problem:

$$Q^{\max} = \begin{cases} Q(T_{1\mathrm{S}}) \to \min \\ T_{\mathrm{IND}i}(T_{1\mathrm{S}}) \geq T_{\mathrm{IND}i}^{\max} \end{cases}. \tag{8}$$

Fig. 2 represents the penalty function curve of heat energy consumption R_2.

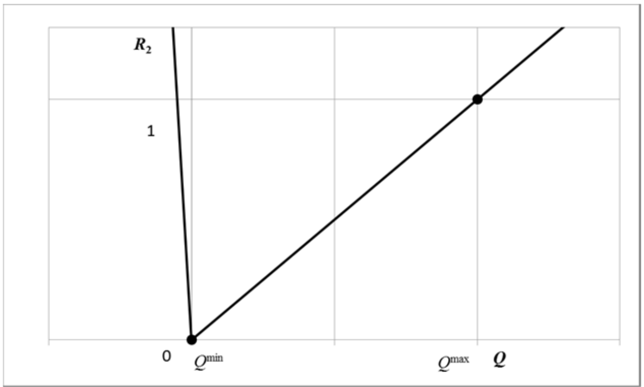

Fig. 2. The penalty function curve of heat energy consumption.

Using penalty functions of Eq. 5 and Eq. 6 the optimization problem of Eq. 4 can be reduced to the optimization problem described by the following cost function:

$$\alpha \cdot R_2(Q(T_{1\mathrm{S}})) + (1-\alpha) \cdot \frac{1}{N}\sum_{i=1}^{N} R_1(T_{\mathrm{IND}i}(T_{1\mathrm{S}})) \to \min, 0 \leq \alpha \leq 1, \tag{9}$$

where α is a coefficient identifying priority of optimization tasks. If α equals 1, heat energy economy optimization problem is solved according to Eq. 6. In this case optimization problem of Eq. 6 can be reduced to the optimization problem of Eq. 7. If α equals 0, comfortable indoor temperature optimization problem is solved according to Eq. 5.

3. Model predictive control

The approach proposed describes optimization of temperature supplied by one heat plant T_{1S}. So, the task of Eq. 9 is a one-dimensional optimization problem. Powell's method was employed to solve the optimization problem. Fig. 3 represents the block diagram for an iteration of optimization problem solution.

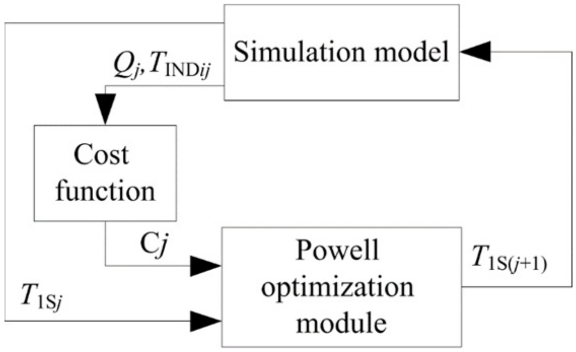

Fig. 3. The block diagram for an iteration of optimization problem solution.

In *j*-step of the block diagram the simulation model calculates the amount of heat energy Q_j produced by the heating plant and mean indoor temperatures of *i*-building T_{INDij} using Eq. 3. The values obtained by the simulations are substituted in cost function Eq. 9. The estimated cost function value is transferred to the optimization module which determines the power plant supply temperature for the next iteration of Powell's method. The initial value of heat plant supply temperature T_{1S0} is obtained using preset supply temperature curve depending on outdoor temperature.

Solution to the optimization problem will enable to put into effect model predictive control (MPC) under which the optimization block using simulation calculates temperature correction of supply temperature for the heating plant. Fig. 4 represents the block diagram of model predictive control. On the block diagram Q is the total heat energy consumed by the heating system. T_{INDi} corresponds to the mean indoor temperature of each consumer, T_1 is the optimized supply temperature, T_{1S0} is the initial supply temperature, T_{1C} is a supply temperature correction which is calculated by the optimization module using the proposed method with the help of the simulation model.

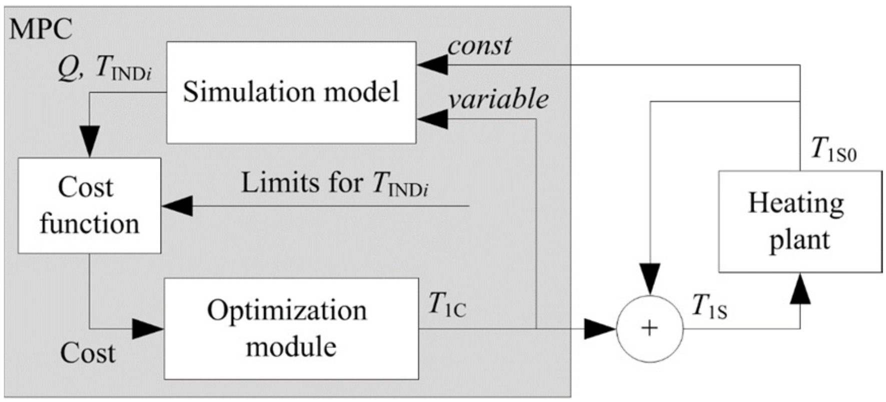

Fig. 4. The block diagram of model predictive control.

4. Simulation experiment

District heating model of the South Ural State University was used to validate the proposed optimization approach. Temperature optimization was performed for heating subsystem which includes 1 heating plant, 4 consumers with automated IHS and 3 consumers without automated IHS. Three outdoor temperature values were considered: -10 °C, -20 °C, -30 °C. Three optimization scenarios were performed:

- Temperature optimization was not performed. Supply temperature was calculated using control curve of the heating plant depending on outdoor temperature.
- Temperature optimization was performed using Eq. 9 while priority coefficient α is equal 1. In this case the purpose of optimization performed is maximizing heat energy economy while maintaining the minimum indoor temperature requirements for each building.
- Temperature optimization was performed using Eq. 9 while priority coefficient α is equal 0.5. In this case the purposes of optimization performed are both maximizing heat energy economy and maintaining the most comfortable indoor temperature for each building.

Optimization and simulations are performed using block diagram language VisSim [20].

Table 1 represents the optimization results. It should be noticed that supply temperature optimization performed using the approach proposed affects consumers without automated IHS greater than consumers with automated IHS which have its own control curves. So, indoor temperature simulation results are under consideration in table 1 only for consumers without automated IHS.

Table 1. The optimization results.

Optimization scenario using simulations		Outdoor temperature, ^{0}C	Without optimization according to heat plant control curve	Heat energy economy optimization (α=1)	Heat energy economy and indoor temperature optimization (α=0.5)
Heating plant supply temperature T_{1S}, ^{0}C		-30	95.0	94.9	96.1
		-20	85.0	80.0	81.0
		-10	75.0	65.1	65.9
Indoor temperature for buildings without IHS, ^{0}C	Academic building 3-D (T_{IND} range is 20-24 ^{0}C)	-30	20.2	20.2	20,7
		-20	22.3	20.1	20,6
		-10	24.3	20.0	20,4
	Hangars (T_{IND} range is 18-22 ^{0}C)	-30	19.5	19.5	20,0
		-20	21.7	19.6	20,0
		-10	23.8	19.6	20,0
	Valeology building (T_{IND} range is 20-24 ^{0}C)	-30	20.1	20.0	20,5
		-20	22.1	20.0	20,4
		-10	24.1	20.0	20,4
Total heat energy production Q, Gcal/h		-30	4.169	4.167	4.189
		-20	3.454	3.367	3.384
		-10	2.742	2.554	2.575
Heat economy in the case of optimization, %		-30	-	0.06	-0.48
		-20	-	2.54	2.02
		-10	-	6.85	6.10

The results show that more comfortable indoor temperature as a whole is reached using optimization which takes into account both indoor comfortable temperatures and heat energy economy requirements. But due to lower indoor temperature heat energy consumption is lower in the case of optimization which purpose is heat energy economy and maintaining of minimum comfort requirements.

5. Summary

The optimization method offered is of special interest for district heating systems where central temperature control strategy is applied and some facilities don't have their own automated IHS. The method allows calculating the heating plant supply temperature, which being maintained will result in the most comfortable indoor temperature of consumers in the heating system as a whole.

It is worth mentioning that the simulation model used to assess the heating system state variables can be designed and run in any simulation environment for physics and engineering involved in exchange of input data and results of heating plant and consumers simulation using a third party software.

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References

[1] A. Nuorkivi, District heating and cooling policies worldwide, in: R. Wiltshire, Advanced district heating and cooling (DHC) systems, Woodhead Publishing, 2015, pp. 17–41.
[2] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J.E. Thorsen, F. Hvelplund, B.V. Mathiesen, 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems, Energy. 68 (2014) 1–11.
[3] M. Brand, A. Della Rosa, S. Svendsen, Energy-efficient and cost-effective in-house substations bypass for improving thermal and DHW (domestic hot water) comfort in bathrooms in low-energy buildings supplied by low-temperature district heating, Energy. 67 (2014) 256–267.
[4] I. Oliker, Steam turbines for cogeneration power plants, J. Eng. Power. 102 (1980) 482–485.
[5] H. Madsen, K. Sejling, H.T. Sogaard, O.P. Palsson, On flow and supply temperature control in district heating systems, Heat Recovery Systems and CHP. 14 (1994) 613–620.
[6] B. Bohm, P.O. Danig, Monitoring the energy consumption in a district heated apartment building in Copenhagen, with specific interest in the thermodynamic performance, Energy and Buildings. 36 (2004) 229–236.
[7] M. Iacob, G.D. Andreescu, N. Muntean, SCADA system for a central heating and power plant, Proceedings of the 5th International Symposium on Applied Computational Intelligence and Informatics. Timisoara, 2009, pp. 159–164.
[8] A. Zabasta, V. Seļmanovs, N. Kunicina, L. Ribickis, Wireless sensor networks for optimization of district heating, Journal of Energy and Power Engineering. 7 (2013) 1362–1369.
[9] D. Shnayder, V. Abdullin, A WSN-based system for heat allocating in multi-flat buildings, 2013 36th International Conference on Telecommunications and Signal Processing. 2013, pp. 181–185.
[10] G. Lukas, V. Swan, I. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renewable and Sustainable Energy Reviews. 13 (2009) 1819–1835.
[11] J. Allegrinia, K. Orehounigb, G. Mavromatidisb, F. Rueschd, V. Dorerb, R. Evins, A review of modelling approaches and tools for the simulation of district-scale energy systems, Renewable and Sustainable Energy Reviews. 52 (2015) 1391–1404.
[12] S. Lima, S. Parkb, H. Chungb, M. Kimc, Y. Baikd, S. Shin, Dynamic modeling of building heat network system using Simulink, Applied Thermal Engineering. 84 (2015) 375–389.
[13] O.P. Palsson, H. Madsen, H.T. Sogaard, Predictor-based optimal control of supply temperature in district heating systems, Proceedings of the International IFAC symposium on control of power plants and power systems. Pergamon, Oxford, 1992, pp. 81–85.
[14] G. Sandou, S. Olaru, Particle Swarm Optimization Based NMPC: An Application to District Heating Networks, Nonlinear Model Predictive Control. 384 (2009) 551–559.
[15] T. Ostergaard, Return temperature optimization by use of smart meters and hydraulic calculations, Proceedings from the 14th International Symposium on District Heating and Cooling. Stockholm, 2014, pp. 549–552.
[16] A. Gros, E. Bozonnet, C. Inard, M. Musy, Simulation tools to assess microclimate and building energy – A case study on the design of a new district, Energy and Buildings, Energy and Buildings, In Press.
[17] D.A. Shnayder, V.V. Abdullin, A.A. Basalaev. Building heating feed-forward control method and its application in South Ural State University academic building , Transactions on Engineering Technologies, World Congress on Engineering and Computer Science 2014, Springer Netherlands, 2015, pp. 69–84.
[18] M.V. Shishkin, D.A. Shnayder, Simulation of thermal-hydraulic systems in VisSim environment, Bulletin of the South Ural State University, Series Computer Technologies, Automatic Control, Radio Electronics, 9 (2004) 120–123.

[19] A.A. Basalaev, Distributed simulation modeling of district heat supply system in VisSim, Bulletin of the South Ural State University, Series Computer Technologies, Automatic Control, Radio Electronics, 13 (2013) 82–87.
[20] D. W.J. Pulle, P. Darnell, A. Veltman, Applied control of electrical drives, real time embedded and sensorless control using VisSim™ and PLECS™, Springer International Publishing, 2015.